A precise new KLOE measurement of $|F_\pi|^2$ with ISR events and determination of $\pi\pi$ contribution to a_μ for $0.592 < M_{\pi\pi} < 0.975$ GeV

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Abstract. The KLOE experiment at the DAΦNE ϕ-factory has performed a new precise measurement of the pion form factor using Initial State Radiation events, with photons emitted at small polar angle. Results based on an integrated luminosity of 240 pb^{-1} and extraction of the $\pi\pi$ contribution to a_μ in the mass range $0.35 < M^2_{\pi\pi} < 0.95$ GeV^2 are presented. The new value of $a^{\pi\pi}_\mu$ has smaller (30%) statistical and systematic error and is consistent with the KLOE published value (confirming the current disagreement between the standard model prediction for a_μ and the measured value).

Keywords: Hadronic cross section, initial state radiation, pion form factor, muon anomaly
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INTRODUCTION

'The anomalous magnetic moment of the muon has recently been measured to an accuracy of 0.54 ppm [1]. The main source of uncertainty in the value predicted [2] in the Standard Model is given by the hadronic contribution, a^{hlo}_μ, to the lowest order. This quantity is estimated with a dispersion integral of the hadronic cross section measurements.

In particular, the pion form factor, F_π, defined via $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta^3_\pi(s)|F_\pi(s)|^2$, accounts for $\sim 70\%$ of the central value and for $\sim 60\%$ of the uncertainty in a^{hlo}_μ.

The KLOE experiment already published [3] a measurement of $|F_\pi|^2$ with the method described below, using an integrated luminosity of 140 pb^{-1}, taken in 2001, henceforth referred to as KLOE05, with a fractional systematic error of 1.3%.

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[1] F. Ambrosino, A. Antonelli, M. Antonelli, F. Archilli, C. Bacci, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, S. Bocchetta, F. Bossi, P. Branchini, P. Campana, G. Capon, T. Capussela, F. Ceradini, F. Cesario, S. Chi, G. Chiefari, P. Ciambrone, F. Crucianelli, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, A. Denig, A. Di Domenico, C. Di Donato, B. Di Micco, A. Doria, M. Dreucci, G. Felici, A. Ferrari, M. L. Ferrer, S. Fiore, C. Forti, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Gorini, E. Graziani, W. Kluge, V. Kulikov, F. Lacava, G. Lanfranchi, J. Lee-Franzini, D. Leone, M. Martemianov, M. Martini, P. Massarotti, W. Mei, S. Meola, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, F. Perfetto, M. Primavera, P. Santangelo, G. Saracino, B. Sciascia, A. Sciubba, A. Sibidanov, T. Spadaro, M. Testa, L. Tortora, P. Valente, G. Venanzoni, R. Versaci, G. Xu.

MEASUREMENT OF $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ AT DAΦNE

DAΦNE is an e^+e^- collider running at $\sqrt{s} \simeq M_\phi$, the ϕ meson mass, which has provided an integrated luminosity of about 2.5 fb^{-1} to the KLOE experiment up to year 2006. In addition, about 250 pb^{-1} of data have been collected at $\sqrt{s} \simeq 1$ GeV, in 2006. Present results are based on 240 pb^{-1} of data taken in 2002 (3.1 Million events) [4]. The KLOE detector consists of a drift chamber [5] with excellent momentum resolution ($\sigma_p/p \sim 0.4\%$ for tracks with polar angle larger than 45°) and an electromagnetic calorimeter [6] with good energy ($\sigma_E/E \sim 5.7\%/\sqrt{E\ [\mathrm{GeV}]}$) and precise time ($\sigma_t \sim 54\ \mathrm{ps}/\sqrt{E\ [\mathrm{GeV}]} \oplus 100\ \mathrm{ps}$) resolution.

At DAΦNE, we measure the differential spectrum of the $\pi^+\pi^-$ invariant mass, $M_{\pi\pi}$, from Initial State Radiation (ISR) events, $e^+e^- \to \pi^+\pi^-\gamma$, and extract the total cross section $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-}$ using the following formula [7]:

$$s\,\frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M^2_{\pi\pi}} = \sigma_{\pi\pi}(M^2_{\pi\pi})\; H(M^2_{\pi\pi})\;, \tag{1}$$

where H is the radiator function. This formula neglects Final State Radiation (FSR) terms (which are properly taken into account in the analysis).

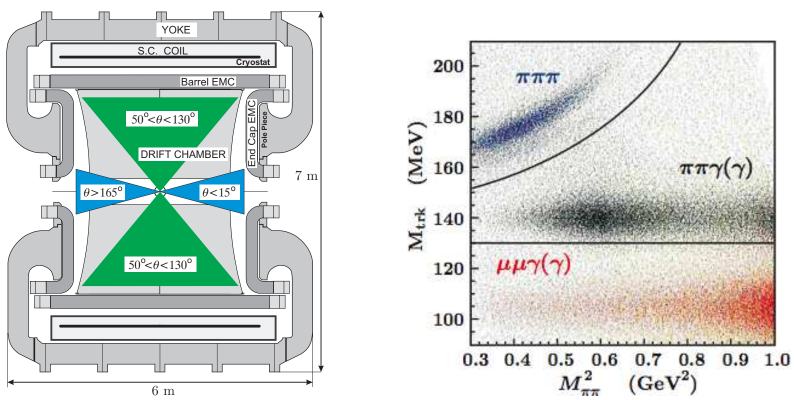

FIGURE 1. Left: Fiducial volume for the small angle photon (narrow cones) and for the the pion tracks (wide cones). Right: Signal and background distributions in the M_{Trk}-$M^2_{\pi\pi}$ plane; the selected area is shown.

In the *small angle* analysis, photons are emitted within a cone of $\theta_\gamma < 15°$ around the beam line (narrow blue cones in Fig. 1 left). The two charged pion tracks have $50° < \theta_\pi < 130°$. The photon is not explicitly detected and its direction is reconstructed by closing the kinematics: $\vec{p}_\gamma \simeq \vec{p}_{miss} = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$. The separation of pion and photon selection regions greatly reduces the contamination from the resonant process $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$, in which the π^0 mimics the missing momentum of the photon(s) and from the final state radiation process $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{FSR}}$. Since ISR-photons are mostly collinear with the beam line, a high statistics for the ISR signal events remains. On the other hand, a highly energetic photon emitted at small angle forces the pions also to be at small angles (and thus outside the selection cuts), resulting in a kinematical suppression of events with $M^2_{\pi\pi} < 0.35$ GeV^2. Residual contamination from the processes $\phi \to \pi^+\pi^-\pi^0$ and $e^+e^- \to \mu^+\mu^-\gamma$ are rejected by cuts in the kinematical variable *track-*

mass, [2] see Fig. 1 right. A particle ID estimator, based on calorimeter information and time-of-flight, is used to suppress the high rate of radiative Bhabhas.

EVALUATION OF $|F_\pi|^2$ AND $a_\mu^{\pi\pi}$

The $\pi\pi\gamma$ differential cross section is obtained from the observed spectrum, N_{obs}, after subtracting the residual background events, N_{bkg}, and correcting for the selection efficiency, $\varepsilon_{sel}(M^2_{\pi\pi})$, and the luminosity, $\mathscr{L}$:

$$\frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M^2_{\pi\pi}} = \frac{N_{obs} - N_{bkg}}{\Delta M^2_{\pi\pi}} \frac{1}{\varepsilon_{sel}(M^2_{\pi\pi})\ \mathscr{L}} . \tag{2}$$

In order to correct for resolution effects, the differential cross section is unfolded using the Bayesian method described in [8]. The integrated luminosity, $\mathscr{L}$, is obtained [9] from the observed number of Bhabha events, divided by the effective cross section evaluated from the Monte Carlo generator `Babayaga@NLO` [10, 11].

The cross section $\sigma_{\pi\pi}(M^0_{\pi\pi})$ is obtained by accounting for final state emission (which shifts $M_{\pi\pi}$ to the virtual photon mass $M^0_{\pi\pi}$) and dividing the $\pi^+\pi^-\gamma$ cross section by the radiator function H (obtained from `Phokhara` [12, 13, 14, 15, 16] by setting pion form factor $F_\pi = 1$) as in Eq. 1.

The *bare* cross section $\sigma^0_{\pi\pi}$, inclusive of FSR, needed for the $a_\mu^{\pi\pi}$ dispersion integral, is obtained after removing vacuum polarization, VP, effects [17]. Tab. 1 left shows the list of fractional systematic uncertainties of $a_\mu^{\pi\pi}$ in the mass range $0.35 < M^2_{\pi\pi} < 0.95$ GeV^2.

Tab. 1 right shows the good agreement amongst KLOE results, and also with the published CMD-2 and SND values. They all agree within one standard deviation.

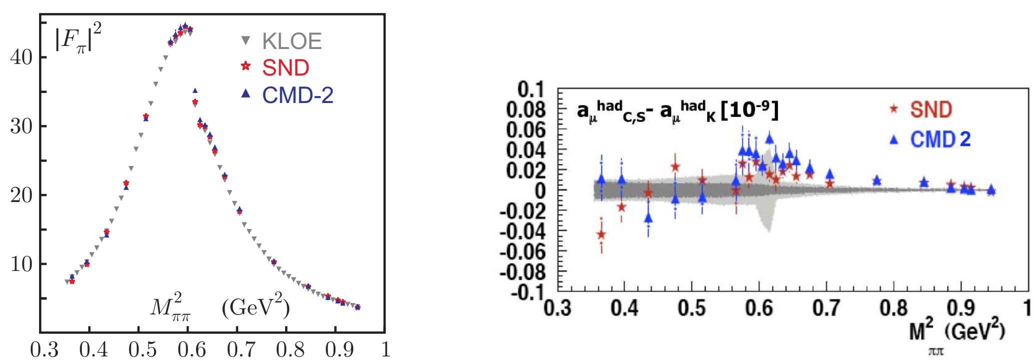

FIGURE 2. Left: Comparison of the pion form factor measured by CMD-2, SND and KLOE, where for this latter only statistical errors are shown. Right: Absolute difference between the dispersion integral value (in each energy bin) evaluated by CMD-2 or SND respect to KLOE. The light (dark) band represents KLOE statistical (statistical$\oplus$systematic) errors.

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[2] Defined under the hypothesis that the final state consists of two charged particles with equal mass M_{Trk} and one photon.

TABLE 1. Left: Systematic errors on the extraction of $a_\mu^{\pi\pi}$ in the mass range $0.35 < M_{\pi\pi}^2 < 0.95$ GeV^2. Right: Comparison among $a_\mu^{\pi\pi}$ values.

Reconstruction Filter	negligible
Background subtraction	0.3 %
Trackmass/Miss. Mass	0.2 %
π/e-ID	negligible
Tracking	0.3 %
Trigger	0.1 %
Unfolding	negligible
Acceptance (θ_{miss})	0.2 %
Acceptance (θ_π)	negligible
Software Trigger (L3)	0.1 %
Luminosity ($0.1_{th} \oplus 0.3_{exp}$)%	0.3 %
$\sqrt{s}$ dependence of H	0.2 %
Total experimental systematics	0.6 %
Vacuum Polarization	0.1 %
FSR resummation	0.3 %
Rad. function H	0.5 %
Total theory systematics	0.6 %

$a_\mu^{\pi\pi} \times 10^{10}$ $0.35 < M_{\pi\pi}^2 < 0.95$ GeV^2	
KLOE05 [3, 18]	$384.4 \pm 0.8_{\text{stat}} \pm 4.6_{\text{sys}}$
KLOE08 [4]	$387.2 \pm 0.5_{\text{stat}} \pm 3.3_{\text{sys}}$
$a_\mu^{\pi\pi} \times 10^{10}$ $0.630 < M_{\pi\pi} < 0.958$ GeV	
CMD-2 [19]	361.5 ± 5.1
SND [20]	361.0 ± 3.4
KLOE08 [4]	356.7 ± 3.1

Fig. 2 left shows a comparison of $|F_\pi|^2$ (obtained by $\sigma_{\pi\pi}$ after subtraction of FSR (assuming pointlike pions) between CMD-2 [19], SND [20] and KLOE (with only statistical errors). For the energy scan experiments, whenever there are several data points falling in one 0.01 GeV ^{2} bin, we average the values. Fig. 2 right shows the absolute difference the $a_\mu^{\pi\pi}$ values for each energy bin obtained in this analysis and the energy scan experiments. All the experiments are in rather good agreement within errors.

CONCLUSIONS AND OUTLOOK

KLOE has measured the dipion contribution to the muon anomaly, $a_\mu^{\pi\pi}$, in the interval $0.592 < M_{\pi\pi} < 0.975$ GeV, with negligible statistical error and a 0.6% experimental systematic uncertainty. Theoretical uncertainties in the estimate of radiative corrections increase the systematic error to 0.9%. Combining all errors KLOE gives:

$$a_\mu^{\pi\pi}(0.592 < M_{\pi\pi} < 0.975 GeV) = (387.2 \pm 3.3) \times 10^{-10}.$$

This result represents an improvement of 30% on the systematic error with respect to the previous published value from KLOE. The new result confirms the current disagreement between the standard model prediction for a_μ and the measured value, as shown in Fig. 3.

Independent analyses are in progress to:

- extract the pion form factor from data taken at $\sqrt{s} = 1$ GeV, off the ϕ resonance, where $\pi^+\pi^-\pi^0$ background is negligible, by using detected photons emitted at large angle. This analysis, which is very close to be finalized, allows to measure $\sigma_{\pi\pi}$ down to the 2-pion threshold;

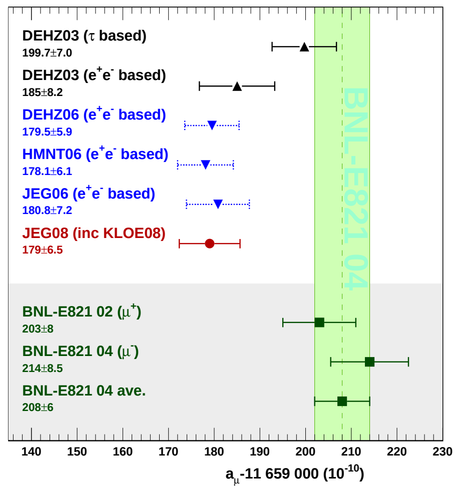

FIGURE 3. Comparison of a_μ from theory and experiment. KLOE08 is included in JEG08 [21]

- measure the pion form factor directly from the ratio, bin-by-bin, of $\pi^+\pi^-\gamma$ to $\mu^+\mu^-\gamma$ spectra [22];
- measure $\sigma_{\pi\pi(\gamma)}$ using the *large angle* analysis at the ϕ peak, which would improve the knowledge of the FSR interference effects (in particular the $f_0(980)$ contribution [23, 24]).

REFERENCES

1. G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. D **73** (2006) 072003
2. F. Jegerlehner, arXiv:hep-ph/0703125
3. A. Aloisio *et al.* [KLOE Collaboration], Phys. Lett. B **606** (2005) 12
4. F. Ambrosino *et al.*, [KLOE Collaboration], Phys. Lett. B **670** (2009) 285
5. M. Adinolfi *et al.*, [KLOE Collaboration] Nucl. Instrum. Meth. A **488** (2002) 51
6. M. Adinolfi *et al.*, [KLOE Collaboration] Nucl. Instrum. Meth. A **482** (2002) 364
7. S. Binner, J. H. Kühn and K. Melnikov, Phys. Lett. B **459** (1999) 279
8. G. D'Agostini, Nucl. Instrum. Meth. A **362** (1995) 487
9. F. Ambrosino *et al.* [KLOE Collaboration], Eur. Phys. J. C **47** (2006) 589
10. C. M. Carloni Calame *et al.*, Nucl. Phys. B **584** (2000) 459
11. G. Balossini *et al.*, Nucl. Phys. B **758** (2006) 227
12. G. Rodrigo, A. Gehrmann-De Ridder, M. Guilleaume and J. H. Kühn, Eur. Phys. J. C **22** (2001) 81
13. J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **25** (2002) 215
14. G. Rodrigo, H. Czyż, J. H. Kühn and M. Szopa, Eur. Phys. J. C **24** (2002) 71
15. H. Czyż, A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **27** (2003) 563
16. H. Czyż, A. Grzelinska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **33** (2004) 333
17. F. Jegerlehner, Nucl. Phys. Proc. Suppl. **162** (2006) 22
18. F. Ambrosino *et al.* [KLOE Collaboration], arXiv:0707.4078
19. R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **648** (2007) 28
20. M. N. Achasov *et al.* [SND Collaboration], J. Exp. Theor. Phys. **103** (2006) 380
21. F. Jegerlehner and A. Nyffeler, arXiv:0902.3360
22. S. E. Müller and F. Nguyen *et al.* [KLOE Collaboration], Nucl. Phys. Proc. Suppl. **162** (2006) 90
23. F. Ambrosino *et al.* [KLOE Collaboration], Phys. Lett. B **634** (2006) 148
24. F. Ambrosino *et al.* [KLOE Collaboration], Eur. Phys. J. C **49** (2007) 473